VOLUME 79 SEPARATE No. 273

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

SEPTEMBER, 1953

CHARTS FOR DESIGNING AIR CHAMBERS FOR PUMP DISCHARGE LINES

by W. E. Evans, and C. C. Crawford

POWER DIVISION

{Discussion open until January 1, 1954}

Copyright 1953 by the AMERICAN SOCIETY OF CIVIL ENGINEERS
Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

THIS PAPER

--represents an effort of the Society to deliver technical data direct from the author to the reader with the greatest possible speed. To this end, it has had none of the usual editing required in more formal publication procedures.

Readers are invited to submit discussion applying to current papers. For this paper the final closing dead line appears on the front cover.

Those who are planning papers or discussions for "Proceedings" will expedite Division and Committee action measurably by first studying the printed directions for the preparation of ASCE technical papers. For free copies of these directions—describing style, content, and format—address the Manager, Technical Publications, ASCE.

Reprints from this publication may be made on condition that the full title of paper, name of author, page reference, and date of publication by the Society are given.

The Society is not responsible for any statement made or opinion expressed in its publications.

This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

CHARTS FOR DESIGNING AIR CHAMBERS FOR PUMP DISCHARGE LINES

W. E. Evans and C. C. Crawford

Synopsis

For controlling pressure surges following interruption of electric power to a pumping plant, the air chamber has certain advantages over other devices used for surge control.

By making simplifying assumptions, surge conditions in a pump discharge line employing an air chamber can be expressed in terms of three other variables.

It is the purpose of this paper to present charts by which the required size of air chamber for a particular pumping installation can be quickly determined for preliminary design purposes. The references, theory, and assumptions necessary for preparation of the charts are given. An example is included to demonstrate the use of the charts.

Introduction

In the design of pumping plants and their discharge lines the transient pressures following interruption of electric power to the pump motor may prove to be objectionable. Corrective measures in the form of surge tanks, surge suppressor valves, air chambers, and other devices are at the disposal of the designer.

After it has been decided that certain types of pressure control devices will meet design requirements, the final choice of the type to be used is usually made as the result of a cost study of the various devices. (The cost of an air chamber is largely determined by its size.) The purpose of this paper is to present a set of data in chart form from which the size of an air chamber can be determined quickly for preliminary design purposes.

As a device for controlling pressure surges in pump discharge lines, the air chamber has certain advantages over both the open-top surge tank and the valve type surge suppressor. Compared with the surge tank, the air chamber can be built smaller, thus simplifying the foundation structure. Also, the air chamber can be built in the form of a long cylinder with its axis parallel to the slope of the ground, which in some cases may drastically reduce foundation costs, and which may make for a better earthquake- and wind-resistant structure. The air chamber can be located near the pump, a location which is not always available to the surge tank. The air chamber can be designed to reduce the downsurges in a pump discharge line, thus preventing collapse of the line and/or water column separation; ordinarily surge suppressor valves are not suitable for performing this important function. The principal disadvantage of the air chamber is that it must be provided with an air supply to replace the compressed air which is constantly going into solution.

An idealized air chamber installation is shown in Figure 1.

Notation

Length of pump discharge pipe line, feet L

Velocity of propagation of water-hammer waves in the pipe line, feet per second . . . . . a

Velcoity of flow in the pipe line, feet per second V

Rate of flow in the pipe line, cubic feet per second . . . . . Q

Cross-sectional area of the pipe line, square feet . . . . . A

Acceleration due to gravity, feet per second^2 . . . . . g

Volume of air in the air chamber at absolute pressure head H* cubic feet C

A fraction, 2, 1, 1/2, 1/4, etc. . . . . f

Absolute pressure head in the pipe line at the base of the air chamber, feet of water . . . . . H*

A coefficient expressing the head loss at entrance to the air chamber such that $K H_o^*$ is the head loss for a flow of Q_o into the chamber . . . . . K

Pipe line characteristic, $\frac{aV_o}{2gH_o^*}$, dimensionless . . . . . ρ^*

Air chamber characteristic, $\frac{2gC_oH_o^*}{AL\,V_o^2}$, dimensionless . . . . . σ^*

Subscript o indicates stead-state conditions prior to power interruption

Subscript n indicates conditions at the nth time interval

The asterisk used in connection with ρ^*, σ^*, and H* indicates that these quantities are based upon absolute, rather than gage heads

The Theory Involved

The transient conditions following power failure to a pumping plant wherein an air chamber and check valve are located near the pump may be described as follows: The head developed by the pump drops rapidly following power interruption and a head differential is thus created across the air chamber outlet. The air chamber starts to discharge into the pipe line to help maintain the head and discharge. Very soon the head produced by the pump is less than that maintained by the air chamber and the check valve closes, then the pump merely coasts to a stop. Water will continue to be discharged from the pipe line at a diminishing rate with the air chamber supplying both the water and the energy. The water in the discharge line will come to rest, reverse its direction, and flow into the air chamber. During the period in which the water is flowing into the air chamber the pressure head in the discharge line will rise above normal operating head and produce the maximum head for the transient. There will follow resurges up and down the pipe line with diminishing intensity.

Angus[a] has demonstrated a graphical method for computing transient hydraulic conditions in a pump discharge line employing an air chamber near the pump. An adaption of the general method described by Angus has been used to make all water-hammer computations performed in preparation of this paper.

Allievi[b] shows that the pressure surges in a pipe line equipped with an air chamber are dependent upon the two parameters ρ^*, and σ^*, when friction is not a consideration. He then shows that without frictional effects the normal size chambers are ineffective in controlling upsurges.

Bergeron[c] in a discussion of Allievi's paper[b] describes a simple, effective, differential orifice for use in conjunction with an air chamber.

In his early work with water-hammer, Allievi described the pipe-line characteristic

$$\rho = \frac{aV_o}{2gH_o},$$

by which all conduits in service can be classed insofar as water-hammer phenomena are concerned. The characteristic is dimensionless and is a function of the ratio of the steady-state kinetic energy to the total potential energy in a unit length of the conduit. When dealing with air chambers the volume of the air is a function of the absolute pressure to which it is subjected, so, in order to facilitate computation, the pipe-line characteristic was changed to

$$\rho^* = \frac{aV_o}{2gH_o^*}$$

where H_o^* is the normal absolute pressure head in the pipe line at the entrance to the air chamber.

The parameter developed by Allievi which pertains to pump discharge lines employing an air chamber is

$$\sigma^* = \frac{2g\,C_o\,H_o^*}{AL\,V_o^2},$$

which is the ratio of steady-state potential energy of the air in the air chamber to the steady-state kinetic energy of the water in the discharge line.

It will be noted that σ^* varies directly with C_o, the initial volume of air in the chamber, so, in order for the air chamber to function as designed, the volume C_o must be maintained at its proper value. The compressed air tends to go into solution. This lost air must be continually replaced to maintain the air chamber in readiness to function properly.

Since frictional resistance to flow is essential to the efficient use of an air chamber in a pump discharge line, a third variable (in addition to Allievi's ρ^* and σ^*) will be used for this study. This variable, K, will be defined so that $K\,H_o^*$ is the total head loss for a flow of Q_o down the pipe line and into the air chamber. A differential orifice similar to that described by Bergeron[c] will be employed to create the head loss. Because of the differential orifice design, the head loss for flow from the air chamber will be less than that for flow into the chamber.

[a]Superscripts refer to items in the bibliography at the end of the paper.

In order to use the graphical method of computation, and to express the results in terms of the proper parameters it is required that an expression be developed to show the relations among σ^*, ρ^*, the flow in the discharge line, and the volume of air in the air chamber. Such an expression can be obtained by algebraic manipulation of the basic relations as follows:

$$\sigma^* = \frac{2C_o H_o^* \varepsilon}{AL V_o^2} = \frac{C_o a}{AL V_o \rho^*}$$

or,

$$C_o = \sigma^* \rho^* \frac{AL V_o}{a} = \sigma^* \rho^* Q_o \left(\frac{L}{a}\right) .$$

Let,

$$c_n = \frac{C_n}{C_o} ,$$

where the subscript n indicates the number of the time interval under study. To fit the graphical solution, the interval of time used will be taken as a fraction of the wave travel time f $\frac{L}{a}$, where f may take values of 2, 1, 1/2, 1/4, etc., as the problem requires. Then,

$$c_1 = \frac{\sigma^* \rho^* Q_o \left(\frac{L}{a}\right) + \left(\frac{Q_1 + Q_o}{2}\right) f \left(\frac{L}{a}\right)}{C_o} ;$$

$$c_1 = c_o + \frac{(Q_1 + Q_o) f \left(\frac{L}{a}\right)}{2 \sigma^* \rho^* Q_o \left(\frac{L}{a}\right)} .$$

Let

$$q_n = \frac{Q_n}{Q_o} ;$$

then,

$$c_1 = c_o + \frac{(q_1 + q_o) f}{2 \sigma^* \rho^*} ,$$

and for time interval n,

$$c_n = c_{n-1} + \frac{(q_n + q_{n-1}) f}{2 \rho^* \sigma^*}$$

the desired relationship. When $2\rho^*$, σ^*, and K are fixed, the above relation makes it possible to compute by the graphical method the complete transient following power interruption. It will be noted that after σ^* and ρ^* are determined, the expression just developed is independent of the value of $\frac{L}{a}$.

Assumptions

For the purposes of making this study the following are assumed:

(a) That there is a check valve on the discharge side of the pump which closes immediately upon power failure
(b) That the air chamber is situated near the pump
(c) That the pressure-volume relationship for the air in the chamber may be expressed by $H^* C^{1.2}$ = a constant
(d) That the ratio of the total head loss for the same flow into and from the air chamber is 2.5:1
(e) That the air in the chamber is subjected to a pressure head of H^*
(f) That the head loss (surface friction and at the orifice) varies with the square of the velocity
(g) That during the transient condition following power failure, the condition of continuity of flow in the discharge line is maintained, i.e., the water column remains intact throughout the length of the line.

These assumptions and simplifications are necessary due to the many variables involved. They permit a solution to the problem that gives usable results. Assumption (a) eliminates the pump characteristics as a consideration, but at the same time it introduces an abrupt wave which must be accounted for throughout the computations. Assumption (c) is a compromise between adiabatic and isothermal expansion, which is justified by the fact that depending upon the installation the actual values range between the two. Assumption (d) can be normally realized through proper orifice design. Theoretically a higher ratio can be obtained, but practically, the lower value is closer to that which will be obtained in ordinary practice. Assumption (e) neglects the static head difference between the water surface in the air chamber and the center line of the pipe below the chamber. Normally, this difference in head is small compared to H^* and the assumption is permissible. Assumption (g) merely limits the study to cases in which the water column remains intact. The study of conditions following breach of the water column is beyond the scope of this paper.

Orifice Design

In restricting the flow into the air chamber to control upsurges there results some restriction upon the flow from the chamber. As may be seen from Figures 3 to 6, the downsurge values at the pump are not increased as much due to an increase in throttling as are the values at the midlength of the pipe line. Normally, the downsurge at the midlength of the pipe line is critical in eliminating water column separation. Then, in order to prevent excessive downsurges in the pipe line it is desirable to keep the outward flow as free as possible while controlling the inward flow.

An effective method for obtaining a high entrance head loss while keeping the exit head loss to a minimum is as follows: For flow from the chamber design the orifice similar to a bellmouth, and for flow into the chamber design a re-entrant tube. This will give discharge coefficients on the order of 1.0 and 0.5, respectively. The corresponding head loss for the same flow would thus be approximately four times as great for inward flow as for outward flow. This head loss ratio of 4 to 1 is difficult to obtain in practice which partly explains the lower ratio used here. Figure 2 shows such an orifice design with actual test results.

The pipe line surface friction loss may be considered as concentrated at the orifice. The actual orifice design should then anticipate this loss. As an example, consider the case where it is desirable to have a total head loss of 50 percent of H_o^* for an inward flow equal to Q_o. The desired total loss for outward flow of Q_o would then be 20 percent of H_o^*, or less. Assume that for a flow of Q_o the pipe line surface friction loss is 5 percent of H_o^*. The orifice would then be designed for head loss of 45 percent of H_o^* for an inward flow of Q_o, and a head loss of 15 percent of H_o^* for outward flow of Q_o. The actual orifice design head loss ratio for inward to outward flow should then be 3 to 1, which can be realized in practice by the suggested method.

The Charts

As discussed previously, certain transient conditions occur after power interruption to the pump motors. For purposes of this study, certain simplifying assumptions have been made. Under the conditions imposed by the assumptions, the entire transient following power failure is completely described as soon as the variables K, $2\rho^*$, and $2\rho^*\sigma^*$ are fixed. In Figures 3, 4, 5, and 6, the maximum upsurges and downsurges have been plotted in terms of these variables. Maximum upsurges and downsurges at the pump and at the midlength of the discharge line are plotted as percentages of H_o^* for various values of the descriptive variables.

Allievi[b] explains that the normal ranges of the parameters ρ^* and σ^* are 0.25 to 2.0 for ρ^* and 2 to 30 for σ^*. These limits have been covered in the charts prepared for this paper. In order to include the effects of friction, the charts cover the range in values of K from 0.0 to 0.7. Values of K greater than 0.7 are ruled out as unnecessary. Because of the great resistance to flow from the chamber, for K = 0.7, large air chambers are needed to control the downsurges, while the upsurges are not greatly reduced. The downsurges can be controlled more efficiently by using smaller air chambers with less throttling.

Ordinarily, when an air chamber is being designed for a pump discharge line these data will be known: L, a, V_o, Q_o, A, H_o^*, and g. From these, $2\rho^*$ can be computed. The allowable maximum surge values may be dictated by specifications, operating conditions, or the profile of the discharge line. With the values of $2\rho^*$ and the maximum allowable surges in mind, from Figures 3, 4, 5, and 6, values of K and $2\rho^*\sigma^*$ may be chosen such that the surge limitations are met. If the allowable surge conditions cannot be satisfied by data obtained from the charts, probably some means other than an air chamber should be used to control the surges. When $2\rho^*\sigma^*$ has been determined, C_o can be computed from the relation

$$C_o = \sigma^* \rho^* 2_o \left(\frac{L}{a}\right) .$$

The volume of the air chamber is then determined by considering that there must be adequate air in the chamber above the upper emergency level (see Figure 8) to control the surges to desirable limits, and enough water in the chamber below the lower emergency level to prevent unwatering. Then with allowances for the volume between the upper and lower emergency levels the total volume of the air chamber can be obtained.

Let C' be the minimum quantity of air which must be maintained in the air chamber, i.e., the volume of the chamber above the upper emergency level.

By adding to this quantity the volume of the chamber between the upper and lower emergency levels (the factors affecting the upper and lower emergency levels will be discussed separately), one obtains the quantity of air in the chamber which will result in the lowest water surface level following power failure. This new volume of air becomes

$C'' = C' +$ volume of air between upper and lower emergency levels.

The downsurge at the pump with this initial volume of air can now be determined from the curves by computing a new value of $2\rho^* \sigma^*$ based upon C'' instead of C'. Then, assuming that this expansion takes place isothermally, the total volume of the air chamber becomes

$$\text{Total air chamber volume} = \frac{C'' H_o^*}{H_o^* - \text{downsurge at pump}}.$$

The various control levels for the water surface in the air chamber insure that at any time the pump is operating there are sufficient quantities of air and water in the chamber to protect the system in the event of power failure. If the water surface rises to the upper emergency level or drops to the lower emergency level the automatic controls shut down the plant.

No universal rule can be given for the location of the compressor "on" and "off" levels with respect to each other. When fixing these levels, consideration should be given the following items, to name a few:

(a) Capacity of the compressor
(b) Size of the air chamber
(c) How frequently the compressor should start and stop
(d) Daily temperature variations which might actuate the compressor controls
(e) How quickly the system is to be put back into operation after a prolonged shutdown

The emergency levels can be located nominal distances above and below the compressor "on" and "off" levels on those installations having only one pump on a discharge line or where manual starting or stopping is provided for individual pumps on the same line. However, if automatic starting and stopping of the individual pumps on the same line are required the emergency levels should be sufficiently removed from the compressor "on" and "off" levels to contain the surges due to starting or stopping the largest of the pumps under the most critical initial conditions.

The data from the surge curves should be used primarily for estimating purposes. In the final design of an installation with an air chamber, individual solutions similar to that shown by Angus[a] should be made to insure that the air chamber will meet design requirements.

Example

An example is included here to demonstrate the use of the charts. The pumping plant shown in Figure 7 is to be fitted with an air chamber of such size that the maximum head at the pump will be limited to 300 feet of water and the maximum negative head in the discharge line will be limited to 25 feet of water.

$$H_o^* = 200 + 34 = 234'$$

$$2\rho^* = \frac{a\,V_o}{g\,H_o^*} = \frac{(2960)(5.093)}{(32.2)(234)} = 2.00$$

Allowable downsurge at midlength of line is

$$198.5 - 175 + 25 = 48.5' = 0.21\ H_o^*.$$

Allowable upsurge at the pump is

$$300 - 200 = 100' = 0.43\ H_o^*.$$

From the charts, Figures 3 to 6, the surge conditions can be met using the values

$$K = 0.3,\ 2\rho^*\sigma^* = 21$$
$$K = 0.5,\ 2\rho^*\sigma^* = 44$$

The volume of air in the chamber will vary directly as σ^*, so the smaller value of $2\rho^*\sigma^* = 21$ will be used. For $2\rho^*\sigma^* = 21$, $2\rho^* = 2$, $K = 0.3$:

The maximum upsurge at the pump = $0.27\ H_o^*$

The maximum downsurge at the pump = $0.32\ H_o^*$

The maximum downsurge at the midlength = $0.21\ H_o^*$.

The surface friction loss in the line for a flow of Q_o is 3 feet of water. The differential orifice should be designed to give a head loss for a flow of 100 cfs into the chamber of

$$(0.3)(234) - 3 = 67 \text{ feet}$$

$$C' = C_o = \sigma^*\rho^* Q_o \left(\frac{L}{a}\right) = \frac{(21)(100)(2000)}{(2)(2960)} = 709 \text{ cu ft}$$

The total volume of the air chamber required to prevent draining assuming the volume between the upper and lower emergency levels to be 20 percent of C' gives $C'' = 1.20\ C'$, and a corresponding value for $2\rho^*\sigma^* = 1.2 \times 21 = 25.2$. The maximum downsurge at the pump with this increased value of $2\rho^*\sigma^*$ is $0.30\ H_o^*$. Then

$$\text{Total air chamber volume} = \frac{1.2 \times 709}{1 - 0.30} = 1{,}215 \text{ cu ft}$$

This is the figure required for preliminary design purposes.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the helpful suggestions given by Mr. John Parmakian, and the work done by Messrs. J. R. Bruggeman and I. I. Pemberton who made most of the individual solutions necessary to the preparation of the air chamber charts and to Mr. R. H. Williams who prepared the drawings.

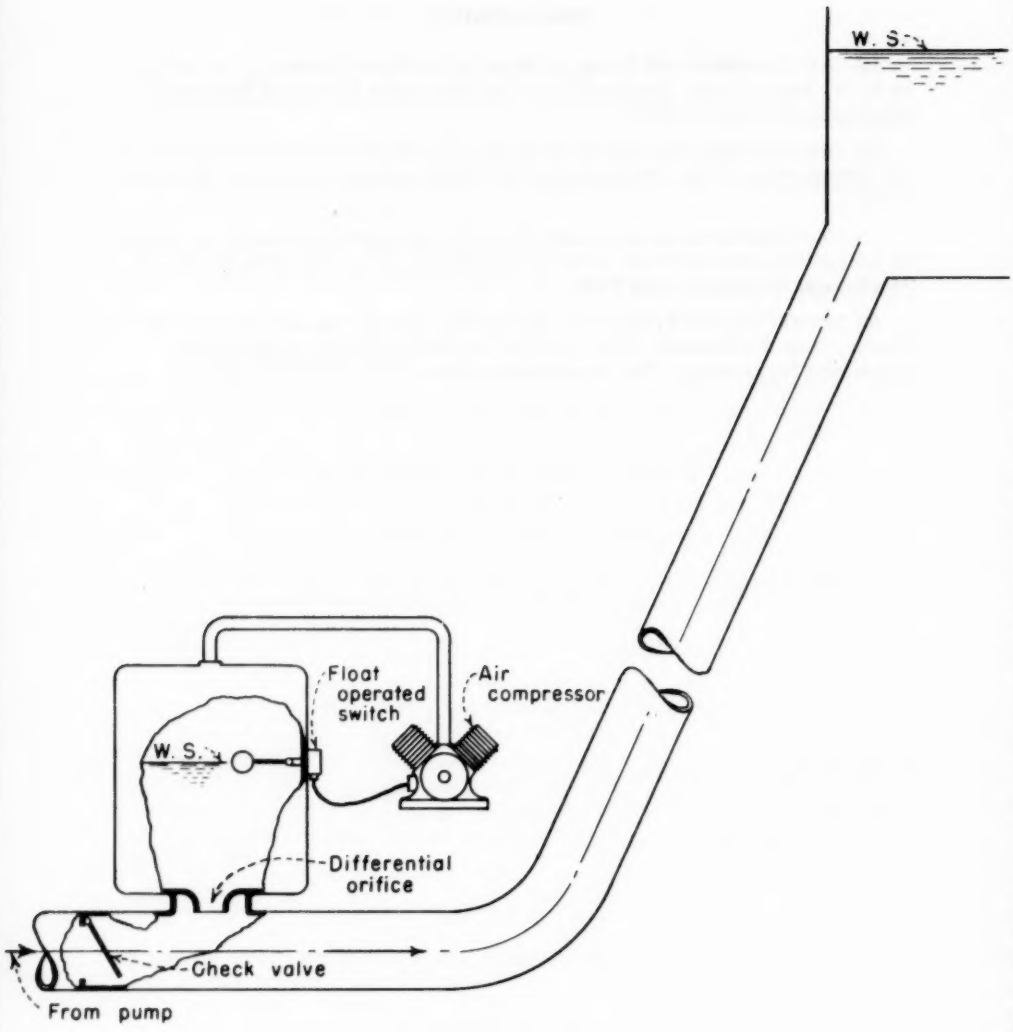
BIBLIOGRAPHY

(a) "Air Chambers and Valves in Relation to Water-Hammer," an article by R. W. Angus, in the Transactions of the American Society of Mechanical Engineers, November 1937.

(b) "Air Chambers for Discharge Pipes," an article by Lorenzo Allievi, in the Transactions of the American Society of Mechanical Engineers, November 1937.

(c) "Air Chambers for Discharge Pipes," a discussion by Louis Bergeron of Lorenzo Allievi's article, in the Transactions of the American Society of Mechanical Engineers, July 1939.

(d) "Protective Air Vessels for Rising Pipe Lines," an article by A. M. Binnie, (also discussions of this article), in the Institution of Mechanical Engineers Proceedings, War Emergency Issues 1-12, 1945, Vol. 153.



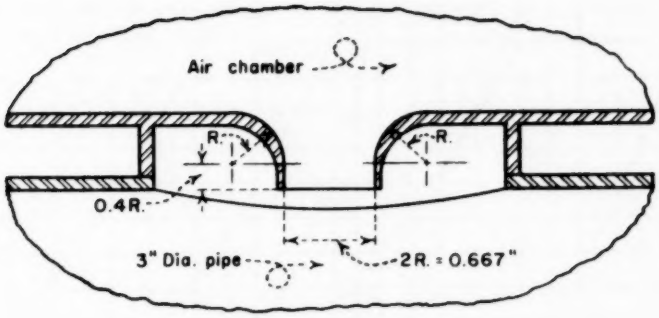
IDEALIZED AIR CHAMBER INSTALLATION ON PUMP DISCHARGE LINE

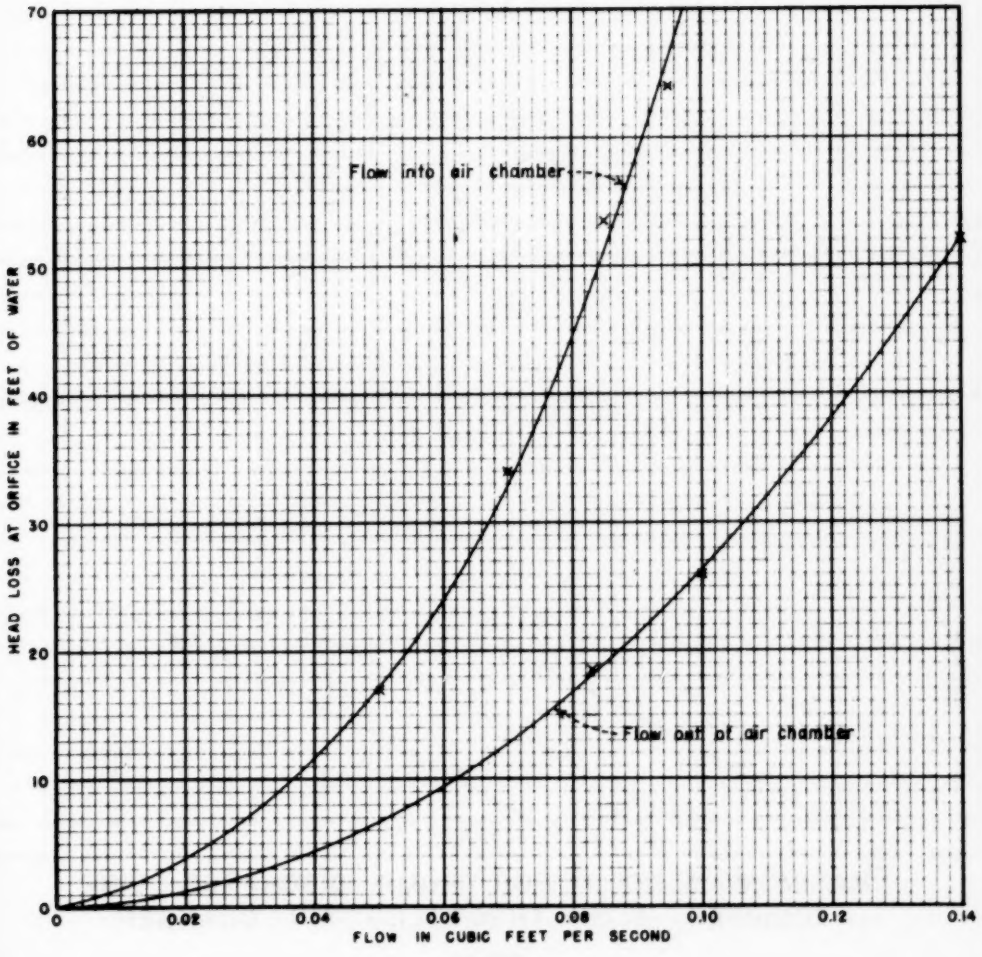
FIGURE 1

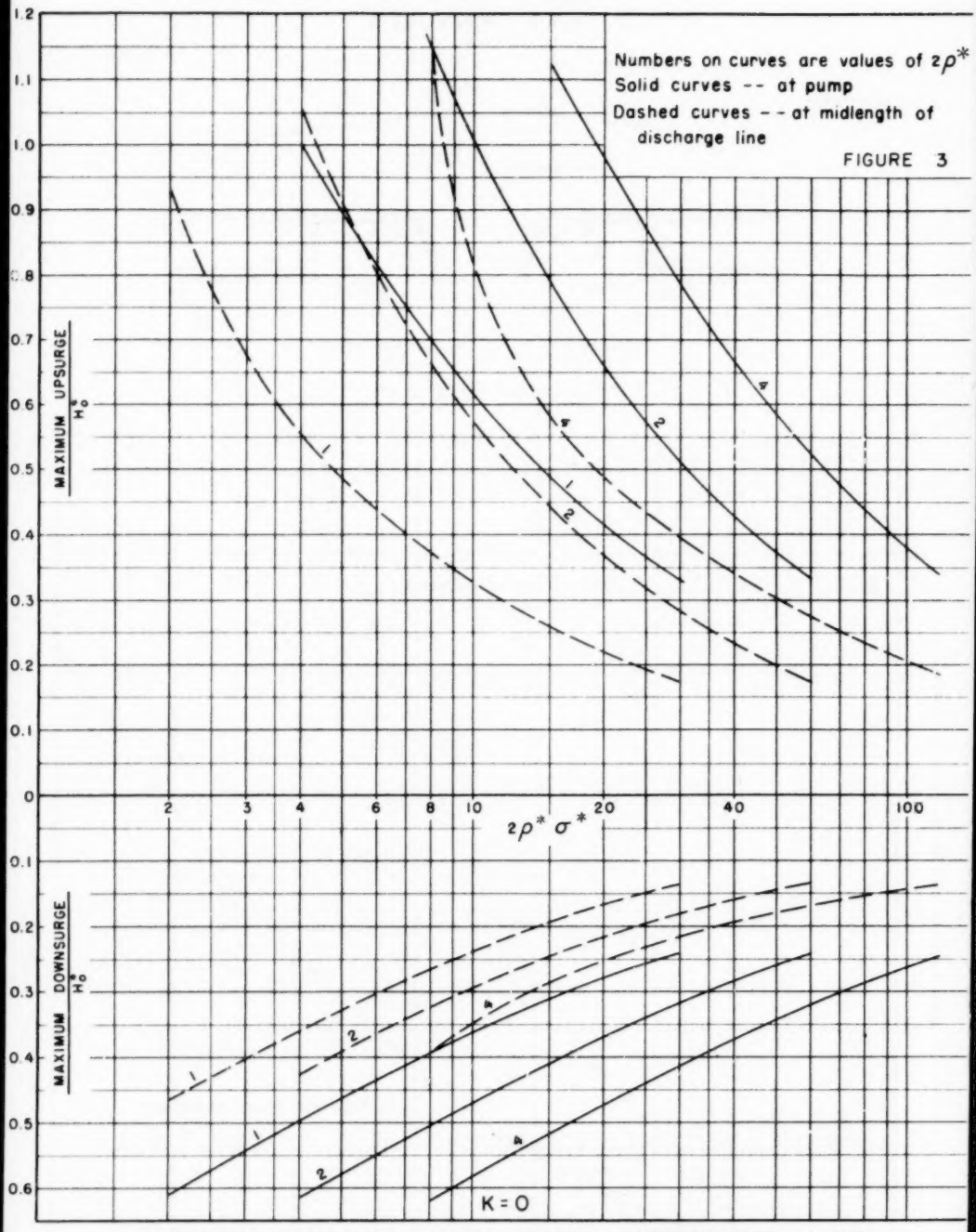
273-10

AIR CHAMBER ORIFICE DESIGN TEST RESULTS

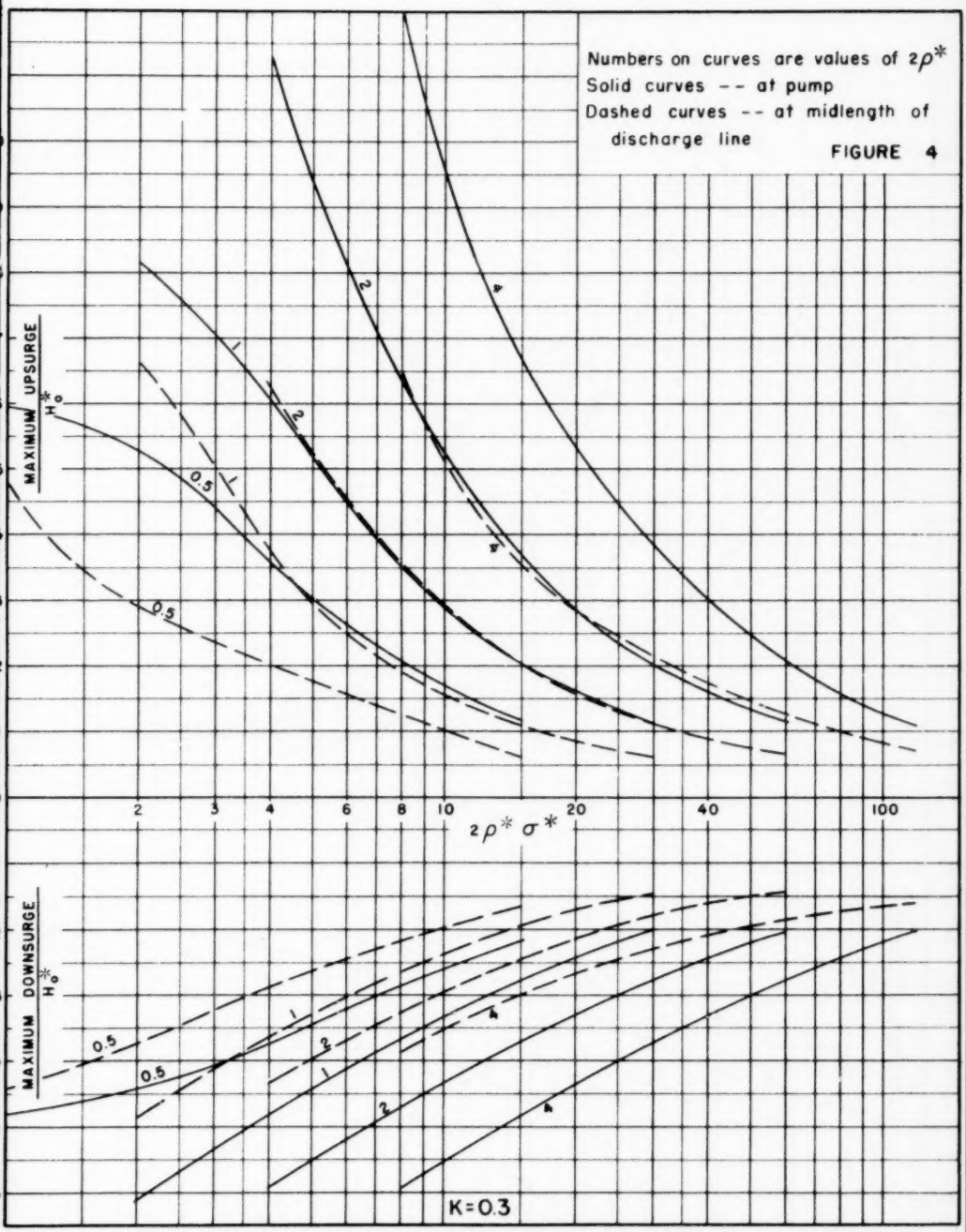
FIGURE 2






Numbers on curves are values of $2\rho^*$
Solid curves -- at pump
Dashed curves -- at midlength of discharge line
FIGURE 3
MAXIMUM UPSURGE / H_0^*
MAXIMUM DOWNSURGE / H_0^*
$2\rho^*\sigma^*$
K = 0

MAXIMUM SURGES FOR PUMP DISCHARGE LINE EQUIPPED WITH THROTTLED AIR CHAMBER



MAXIMUM SURGES FOR PUMP DISCHARGE LINE EQUIPPED WITH THROTTLED AIR CHAMBER

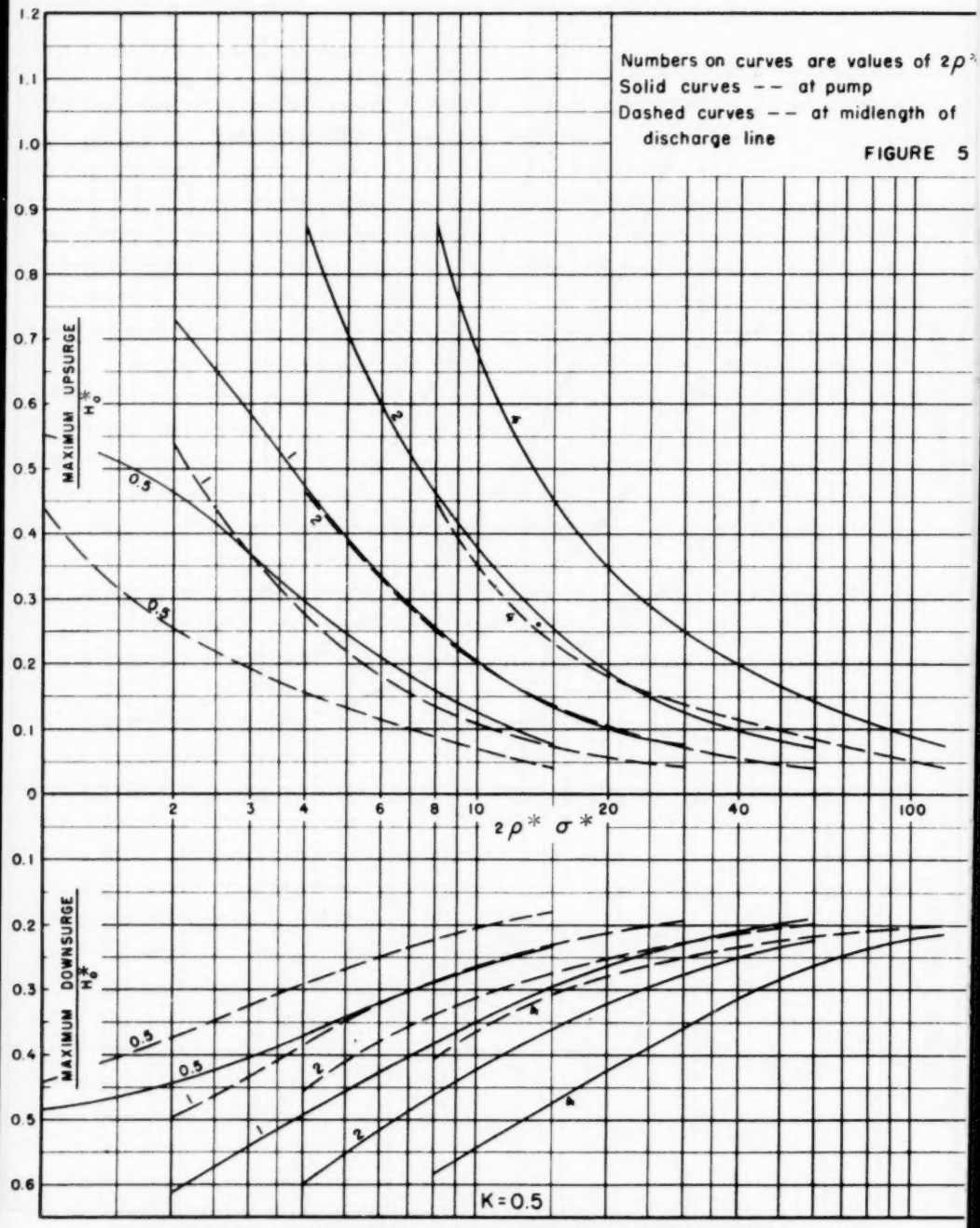
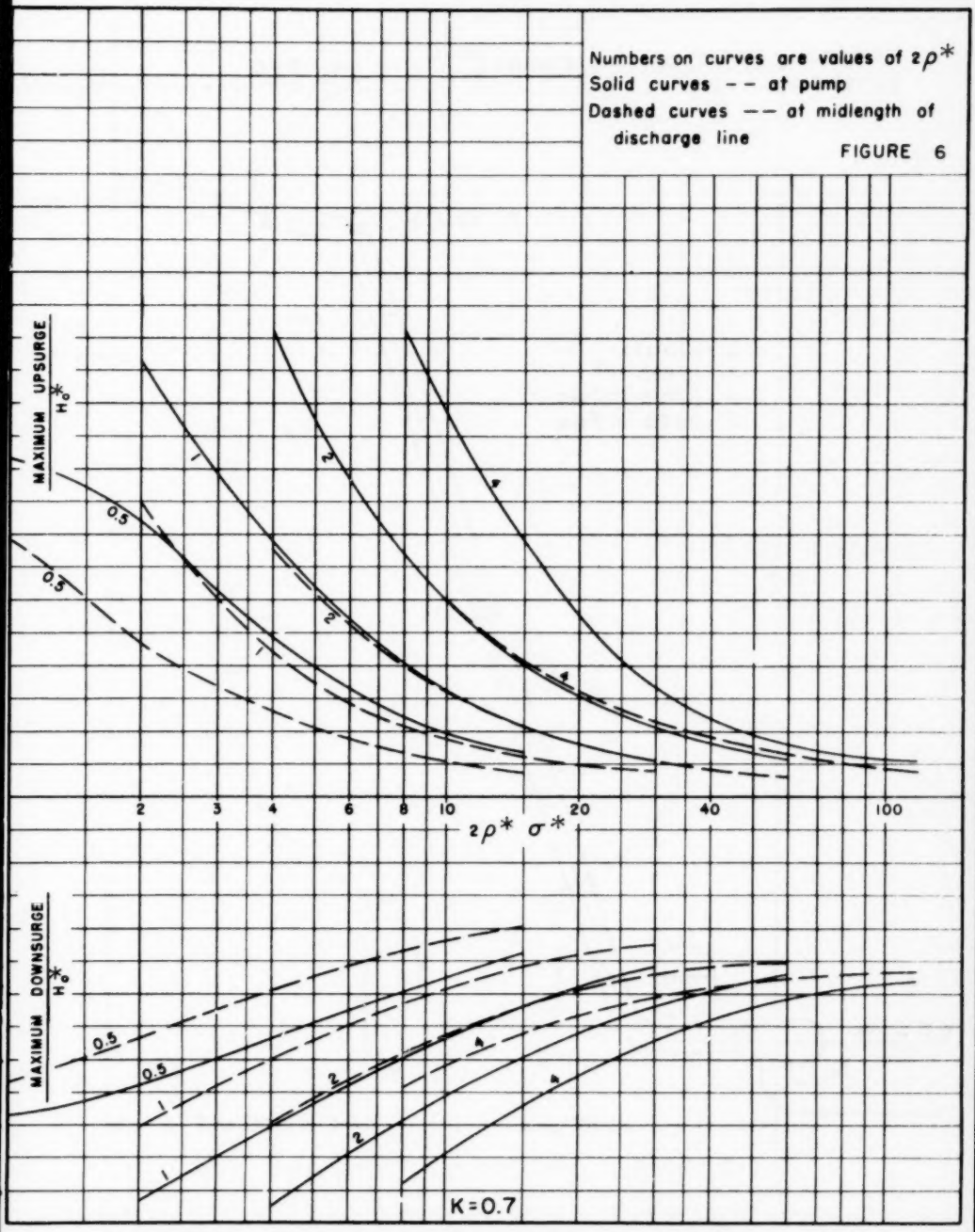

Numbers on curves are values of $2\rho^*$
Solid curves -- at pump
Dashed curves -- at midlength of discharge line
MAXIMUM UPSURGE $\frac{*}{H_0}$
MAXIMUM DOWNSURGE $\frac{*}{H_0}$
$2\rho^* \sigma^*$
K=0.5

FIGURE 5

MAXIMUM SURGES FOR PUMP DISCHARGE LINE EQUIPPED WITH THROTTLED AIR CHAMBER



MAXIMUM SURGES FOR PUMP DISCHARGE LINE EQUIPPED WITH THROTTLED AIR CHAMBER

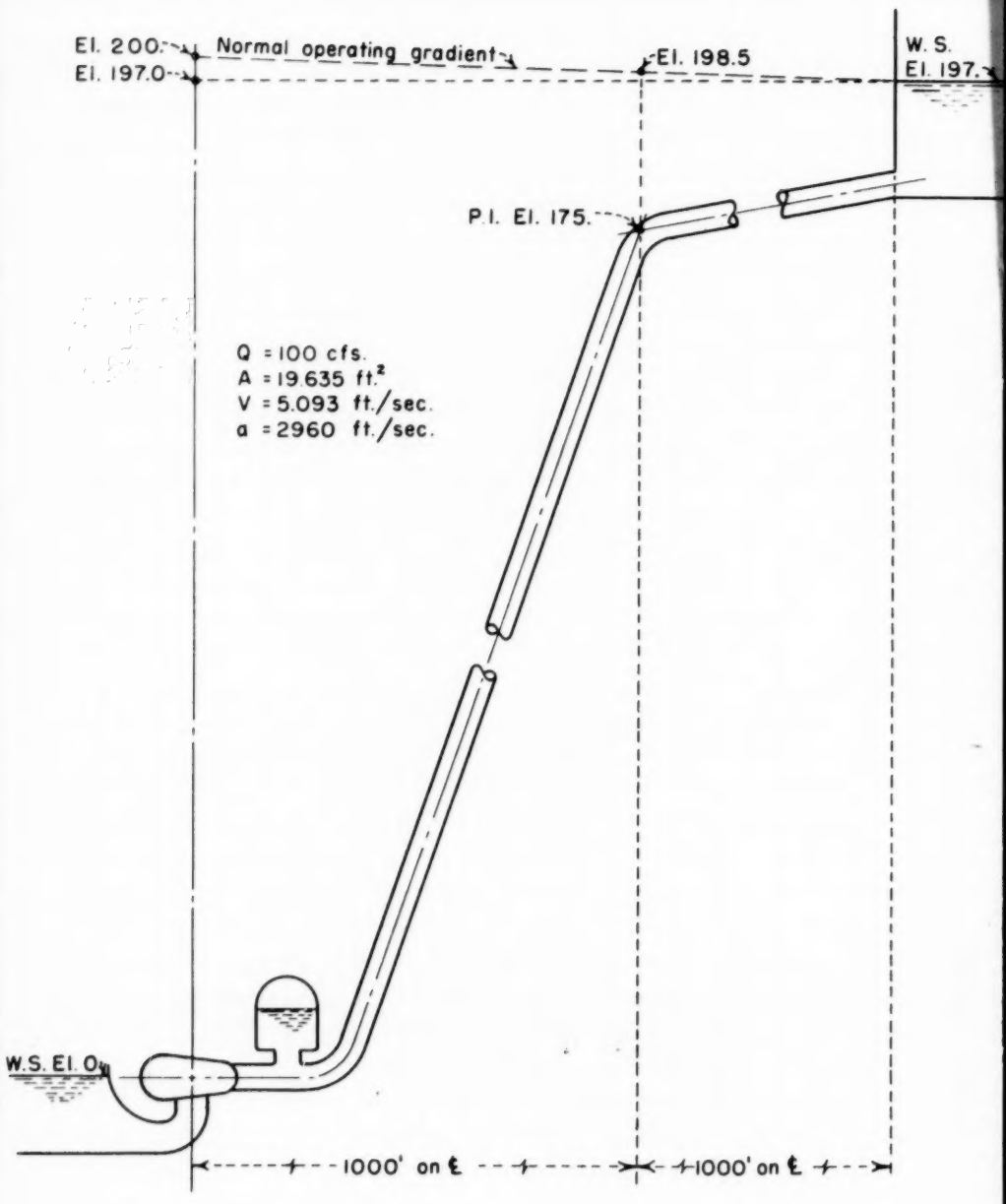
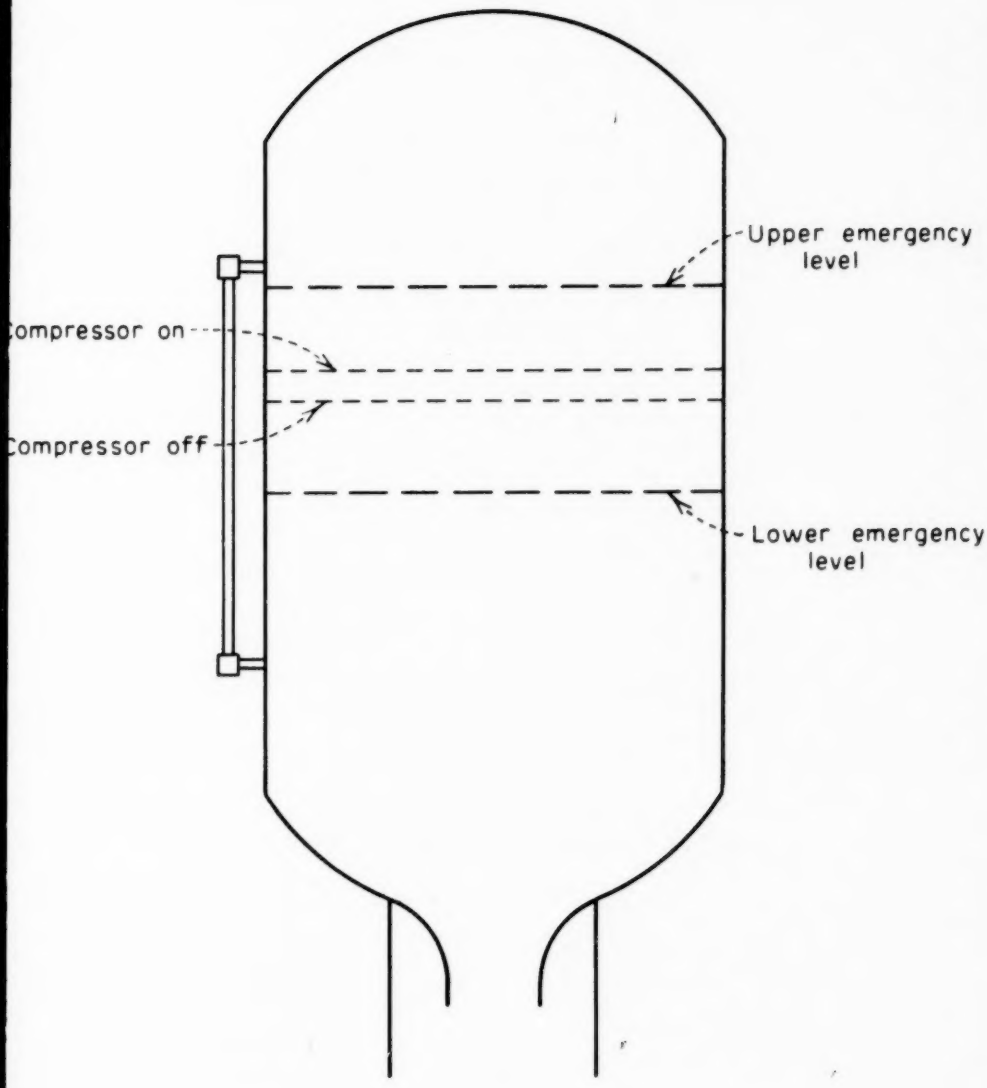


FIGURE 7

273-16



AIR CHAMBER CONTROL LEVELS

FIGURE 8

AMERICAN SOCIETY OF CIVIL ENGINEERS

OFFICERS FOR 1953

PRESIDENT

WALTER LEROY HUBER

VICE-PRESIDENTS

Term expires October, 1953:
GEORGE W. BURPEE
A. M. RAWN

Term expires October, 1954:
EDMUND FRIEDMAN
G. BROOKS EARNEST

DIRECTORS

Term expires October, 1953:
KIRBY SMITH
FRANCIS S. FRIEL
WALLACE L. CHADWICK
NORMAN R. MOORE
BURTON G. DWYRE
LOUIS R. HOWSON

Term expires October, 1954:
WALTER D. BINGER
FRANK A. MARSTON
GEORGE W. McALPIN
JAMES A. HIGGS
I. C. STEELE
WARREN W. PARKS

Term expires October, 1955:
CHARLES B. MOLINEAUX
MERCEL J. SHELTON
A. A. K. BOOTH
CARL G. PAULSEN
LLOYD D. KNAPP
GLENN W. HOLCOMB
FRANGIS M. DAWSON

PAST-PRESIDENTS

Members of the Board

GAIL A. HATHAWAY
CARLTON S. PROCTOR

TREASURER

CHARLES E. TROUT

EXECUTIVE SECRETARY

WILLIAM N. CAREY

ASSISTANT TREASURER

GEORGE W. BURPEE

ASSISTANT SECRETARY

E. L. CHANDLER

PROCEEDINGS OF THE SOCIETY

HAROLD T. LARSEN
Manager of Technical Publications

DEFOREST A. MATTESON, JR.
Assoc. Editor of Technical Publications

PAUL A. PARISI
Editor of Technical Publications

COMMITTEE ON PUBLICATIONS

LOUIS R. HOWSON

FRANCIS S. FRIEL
GLENN W. HOLCOMB
I. C. STEELE
FRANK A. MARSTON
NORMAN R. MOORE

• Readers are urged to submit discussion applying to current papers. Forty free Separates per year are allotted to members. Mail the coupon order form found in the current issue of *Civil Engineering*.